1ир.

NASA TECHNICAL TRANSLATION NASA TT F-13,869

NUMERICAL MODELING OF HEAT TRANSFER BY RADIATION AND CONVECTION IN THE VENUSIAN ATMOSPHERE

V.S. Avduyeskiy, F.S. Zavelevich, M.Ya. Marov,
A.I. Noikina, and V.I. Polezhayev

Translation of "Chislennoye modelirovanie luchisto-konvektivnogo teploobmena v atmosfere venery"

In: Kosmicheskiy Issledovaniya, Vol. 9, No. 2: 280-291 (1971),

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 OCTOBER 1971

N72-14850 (NASA-TT-F-13869) NUMERICAL MODELING OF HEAT TRANSFER BY RADIATION AND CONVECTION IN THE VENUSIAN ATMOSPHERE V.S. Avduyeskiy, et al (Scripta Technica, Inc.) Oct. 1971 17 p CSCL 03B G3/30

Unclas
12016

(CATEGORY)

NUMERICAL MODELING OF HEAT TRANSFER BY RADIATION AND CONVECTION IN THE VENUSIAN ATMOSPHERE

V.S. Avduyevskiy, F.S. Zavelevich, M.Ya. Marov, A.I. Noikina, and V.I. Polezhayev

ABSTRACT: An approximate analysis of heat transfer in the Venusian atmosphere is presented. The radiant fluxes are calculated, and a model of convective flow is developed for the lower layer of the atmosphere; the fraction radiative and convective transport in the overall thermal balance of the planet are estimated.

The flights of the unmanned interplanetary space probes Venera 4, 5, and 6 have produced direct measurements of the composition, pressure, temperature, and density of the Venusian atmosphere and allowed the modeling of that atmosphere [1-3]. From these measurements one can form more definite judgements as to the mechanisms responsible for the most characteristic features of the thermal regime on Venus. /280*

In the present paper, which develops the preliminary result reported in [4], we give an approximate analysis of the heat transfer in the Venusian atmosphere. The radiant fluxes are computed, a model of the convective motions in the lower layer of the atmosphere is developed and the roles of radiative and convective transfer in the overall thermal balance of the planet are estimated.

I. RADIATIVE TRANSFER IN THE VENUSIAN ATMOSPHERE

1. Formulation of problem. The radiant fluxes in the atmosphere of Venus were calculated from the height distributions of temperature and pressure measured on the night side, which were extrapolated to the surface of the planet [3]. The profiles of these distributions will henceforth be referred to as the basic profiles. The composition of the atmosphere was assumed, in accordance with [2], to be as follows: 97% carbon dioxide, less than 2% nitrogen, water vapor varying in the range 0.1-1.5% (the latter value is taken as the upper bound).

The assumptions underlying the model are that the solar energy incident on the day side is distributed uniformly over the planet's surface in accordance with $q = q_0(1-A)\cos\varphi/\pi$, where q_0 is the solar constant at the orbit of Venus, A is the planet's integral spherical albedo, and φ is latitude. Since Venus has a very dense atmosphere that stores a large quantity of heat, it was assumed that

*Numbers in the margin indicate pagination in the foreign text.

the temperature distribution is virtually independent on the time of day. It was also assumed that the gas is transparent in the visible region. Since information on the concentrations and characteristic sizes of dust particles on Venus is very uncertain, aerosol and Rayleigh scattering of visible and infrared radiation was neglected.

Radiative transfer was investigated in the infrared (1.3 μ to 20 μ), since it is in this region that the spectral intensity of radiation of the Venusian surface reaches its maximum and the most important rotational and vibrational carbon dioxide and water vapor bands are encountered. The coefficients of absorption for CO_2 and H_2O were borrowed from [5-7]. /281

The coefficients used in this paper describe only the general patterns of the infrared absorption spectrum of the mixture of these gases, which depends in a complex manner on frequency and temperature. This pertains particularly to CO_2, for which, unfortunately, there is partically no information on the shapes and true intensities of the absorption lines and their variations with temperature and pressure in large optical masses. The real temperature and pressure dependences may thus result in blocking of the transparency windows that CO_2 exhibits under normal conditions.

Since the radius of Venus is much larger than the thickness of its atmosphere and the latter's curvature can be disregarded, the problem of finding the radiant fluxes in the planet's atmosphere is naturally reduced to determination of radiant-energy transfer within a plane layer of gas. The equation of radiant energy transfer for monochromatic radiation takes the form

$$\frac{dI_\nu}{dS} = \varkappa_\nu (B_\nu - I_\nu). \quad (1)$$

Here I_ν [$W \cdot \mu/m^2 \cdot sr$] is the spectral intensity of the radiation at each point of beam S, B_ν is that intensity for a black body, and $\varkappa_\nu$ is the coefficient of absorption.

The projection of the spectral flux q_ν onto the normal to the Venusian surface gives, in the plane-layer approximation,

$$q_\nu = q_\nu^+ - q_\nu^-,$$

where q_ν^+ is the "upward-directed" flux, q_ν^- is the "downward-directed" flux, and

$$q_\nu^{(+,-)} = 2\pi \int_0^{\pi/2} I_\nu \cos\vartheta \sin\vartheta \, d\vartheta, \quad (2)$$

ϑ is the angle between an arbitrary beam S and the normal to the surface. The total flux is determined by integrating Eq. (2) over the entire spectral interval

$$q = \int q_\nu \, d\nu. \quad (3)$$

The problem was solved with the following boundary conditions.

At the surface of Venus

$$I_{\nu s} = \varepsilon B_{\nu s} + (1 - \varepsilon) I_{\nu g}, \quad (4)$$

where $B_{\nu s}$ is the spectral intensity of a black body with the temperature of the Venusian surface, $I_{\nu g}$ is the intensity of the radiation from the atmosphere to the surface, and ε is the emissivity of the surface.

We assumed $\varepsilon = 1$ in the calculations. To evaluate the influence of emissivity on the radiant fluxes, we also performed a calculation with $\varepsilon = 0.9$, from which it follows that this departure of the emissivity from unity has little effect on the radiant fluxes.

Given the different hypotheses as to the optical properties of the clouds, let us consider three types of boundary conditions at cloud-layer level:

a) clouds transparent in the infrared;

b) clouds that absorb all infrared radiation;

c) reflecting clouds.

In the latter case, the radiation from the lower layers of the atmosphere is partially reflected from the clouds, and the boundary condition assumes the form

$$I_{\nu s} = p I_{\nu g} + (1 - p) I_{\nu c}, \quad (5)$$

where $I_{\nu g}$ is the intensity of the radiation from the gas to the clouds and p is the reflection coefficient of the clouds (it is assumed that p is independent of angle). /282

The calculations were made for two "model" heights of hypothetical clouds, $h_c = 50$ km with $T_c = 300^\circ$K and $h_c = 70$ km with $T_c = 240^\circ$K.

The problem was solved numerically for the case of selective radiation. Equation (1) was solved by the method of finite differences. To determine the angular distribution of the radiation field, the transfer equation was solved for beams passed at angles $\Delta\vartheta, 2\Delta\vartheta \ldots m\Delta\vartheta$ to the normal. The quantity $\Delta\vartheta$ was taken equal to 15°. The frequency step used in the integration was $\Delta\nu = 0.005\ \mu^{-1}$.

2. Radiant fluxes. As an example, Fig. 1 shows the calculated distribution I_ν in the wave-number range from 0.05 to 0.7 μ^{-1}, as obtained for the basis profiles of temperature T and pressure P. The distributions of radiant

intensity for the dense layers of the atmosphere ($P > 10$ atm) differ insignificantly from the corresponding black-body radiant intensities over the entire frequency ranged studied, except for the region from 0.08 to 0.1 μ^{-1}. The observed increase in I_v in this region results from loss of energy from hotter layers of the atmosphere. The shaded bars in Fig. 1 indicate the CO_2 absorption bands. They occupy a minor part of the spectral range studied. In the presence of CO_2 alone, therefore, the loss of energy from the surface would be extremely large at the values assumed for the absorption coefficients. Addition of water vapor results in heavy screening of the outgoing longwave radiant fluxes over the entire spectral region studied. At the same time, the loss of energy from the lower layers of the atmosphere remains significant for the most probable water content (<1%) when the clouds are assumed transparent in the infrared, so that thermal balance between the radiant fluxes incoming from the sun and outgoing from Venus can be struck only at low values of the planet's integral spherical albedo A.

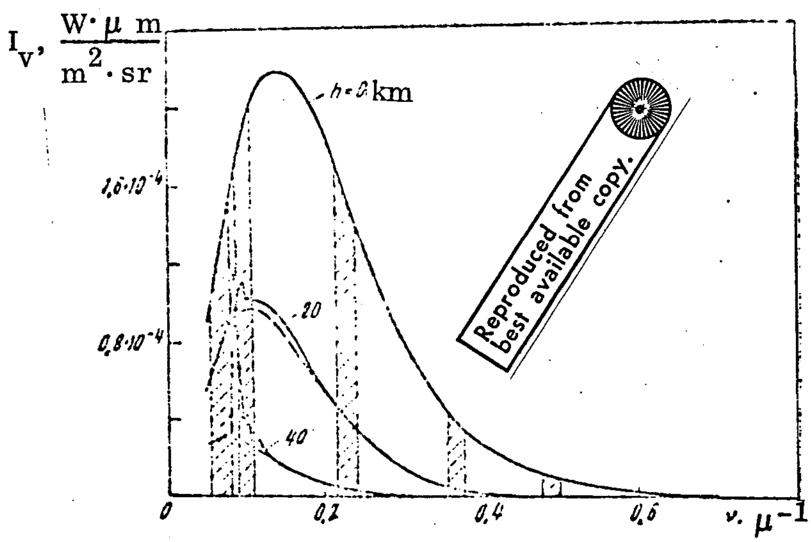

Figure 1. Radiant Intensity I as a Function of the Frequency v.

Figure 2 presents profiles of the radiant fluxes for various atmospheric moisture contents, as computed on the assumption of cloud transparency. The results in Fig. 2 lead us to the conclusion that with transparent clouds and water-vapor content at or below one percent, thermal balance is achieved only at $A \leq 0.6$. The latter is difficult to reconcile with the value $A = 0.77 \pm 0.07$ [8] determined from photometric measurements.

The difference between the heat fluxes incident from the sun and outgoing from the Venusian atmosphere at the most probable A can be understood if it is recognized, firstly, that the shortwave region of the solar spectrum may be absorbed in the lower layers of the atmosphere, with the result that the true temperature profile differs from the basic profile; secondly, that the clouds may absorb and reflect infrared radiation; and, finally, that the real absorption coefficient may differ strongly at high pressures and temperatures from those used. Let us first consider how each of the first two hypotheses would affect the thermal balance of the planet.

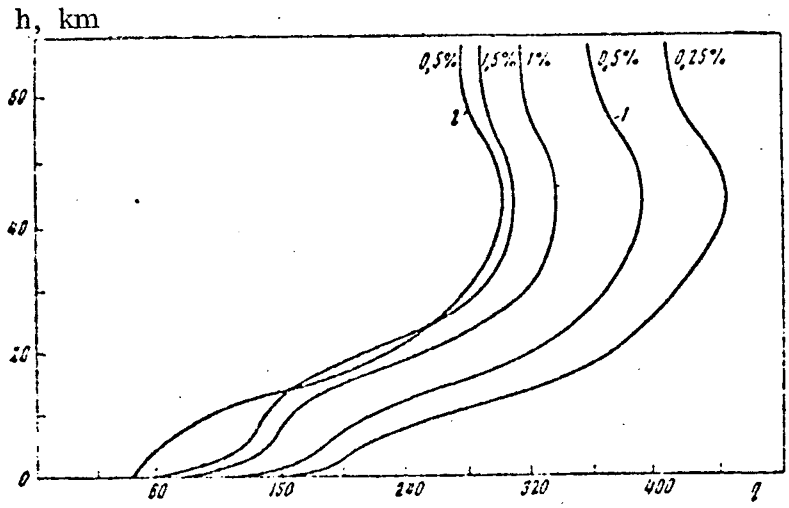

Figure 2. Height Distributions of Radiant Fluxes as Calculated for the Basic T and P Profiles (Transparent Clouds); Radiant-Flux Curves (q in W/m^2).

Figure 2 also shows the height distributions of the radiant fluxes for 0.5% H_2O, as calculated from two temperature profiles corresponding to temperatures $T_s = 730^o$ (1) and $T_s = 670^oK$ (2) at the surface of the planet. We see that at 0.5% H_2O, the radiant fluxes, even when calculated from temperature profile (2), are still much larger than the mean flux from the sun at $A \approx 0.77$ (at latitude $\varphi = 10^o$, the flux from the sun $\sim$ 200 W/m^2). There is little reason for extrapolating the measured temperature values to still lower T_s.

Consider now the influence of cloud optical properties and heights above the surface on the amount of outgoing longwave radiation.

If we draw an analogy to the case of terrestrial clouds, the difference between the radiation from dense opaque clouds and black-body radiation when the fluxes into a hemisphere are examined does not exceed 5-10% in the 4-40-μ spectral interval, except for the 8-12-μ window, where it may reach 15-25% for clouds consisting of water droplets [9].

We see from comparison of the radiant flux curves in the subcloud atmosphere of Venus, as calculated from temperature profile (1) for transparent and black clouds in Fig. 3, that the two extreme hypotheses as to cloud emissivity have little influence on the flux values. These hypotheses affect q only in the immediate vicinity of the cloud layer.

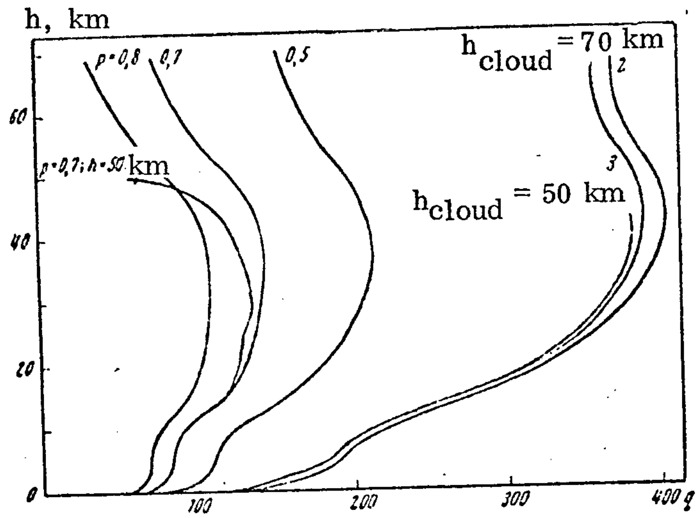

Figure 3. Nature of Radiant Fluxes for Various Cloud Geometric Albedos and Various Types of Clouds:

1) Transparent Clouds; 2) Black Clouds, h_{cl} = 70 km; 3) Black Clouds, h_{cl} = 50 km (C_{H_2O} = 0.5%) (q in W/m^2).

For calculation of radiant fluxes in the Venusian atmosphere, the upper-boundary condition (5) appears most probable. In this case, a certain fraction of the outgoing infrared radiation will be reflected from the clouds, and this may strongly influence the radiant flux values. Since the reflectance of the Venusian clouds for the outgoing thermal radiation is unknown, the calculations were made for four values of the reflection coefficient at the bottom of the clouds (p = 0.8, 0.7, 0.5 and 0). The calculated results appear in Fig. 3. Obviously, if we assume that $p \approx 0.5$, the radiant fluxes calculated from temperature profile (2) can be reconciled with the flux from the sun.

3. Determination of temperature profiles corresponding to radiative equilibrium. We wanted to find the temperature distribution in the Venusian atmosphere that corresponds to purely radiative equilibrium, since convective motions may be set up in the atmosphere by the difference between the radiative and adiabatic temperature gradients. To satisfy the conditions for equilibrium,

it is necessary that

$$q = \frac{q_0(1-A)\cos\varphi}{\pi} = \text{const.}$$

be satisfied at any point in the atmosphere.

In calculating T_{rad} from Eqs. (1)-(3), the boundary condition at the upper boundary was (5) (reflecting clouds), and the values of I_ν^+ at the lower boundary, which were needed to compute the upward fluxes, were determined by adjusting the surface temperature to meet the thermal balance condition at the surface.

As in the case in which conditions (4) are assigned, the gas temperature in the immediate proximity of the surface may differ from the surface temperature of the planet. In the case under consideration, when $\varepsilon = 1$ and the gas layer is optically thick, this difference will obviously be negligibly small.

Figure 4 presents the basic temperature profiles and those calculated on /285
the assumption of radiative equilibrium. We see from this diagram that the radiative equilibrium condition results in a substantial increase in the height gradients of temperature. Especially large gradients, far in excess of adiabatic, are attained at the surface of Venus. Strong convective motions should be generated in this region.

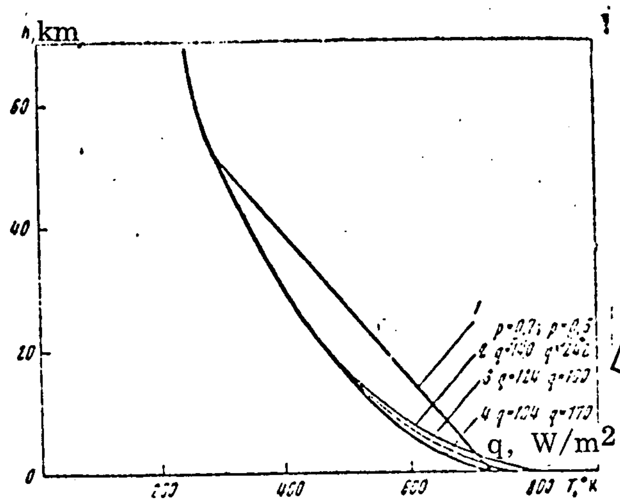

Figure 4. Temperature Profiles:

1) Basic Profile; 2)-4) Radiative Equilibrium Profiles.

II. CONVECTIVE TRANSFER IN THE LOWER ATMOSPHERE OF VENUS

1. Model of convective motions of a compressible gas. Similarity criteria. We see from examination of the height distribution of the radiant fluxes calculated from the measured temperature distribution that thermal equilibrium can be arrived at only with supplementary heat transfer at heights $h \leqslant 40-50$ km.

The fact that the measured temperature profile is nearly adiabatic permits the assumption that the additional upward transfer of heat from the hot lower layers of the atmosphere comes about by natural convection. The considerable depth of the convective zone and the substantial departure of the temperature profile corresponding to radiative equilibrium from the adiabatic profile constitute the basic factors leading to the appearance of this type of convection. Consideration of these factors requires the development of a theoretical model of convective motions in a compressible gas.

The system of similarity criteria that determine the flow and transfer of heat in natural convection in a compressible gas takes the form [10]

$$\mathrm{Ra},\ K,\ C_F,\ \mathrm{Pr},\ \varkappa. \tag{6}$$

Here $\mathrm{Ra} = \mathrm{GrPr}$ is the Rayleigh number, $\mathrm{Pr} = \mu c_p/k$ is the Prandtl number, $\mathrm{Gr} = gL^4 q_w/v^2 kT_1$, is the Grashof number referred to the incoming heat flux q_w, or $\mathrm{Gr} = C_R^2\, q_w^*\, C_F$; $q_w^* = q_w L/kT_1$, where T_1 is the temperature at the upper boundary of the convection cell, C_R is the scale factor, L is the characteristic dimension of the convection region, $C_F = gL/\varkappa RT_1$ is the compressibility criterion, $K = gk/c_p q_w$ is the ratio of the adiabatic temperature gradient g/c_p to the assigned radiative gradient q_w/k, g is the acceleration of gravity, k is the coefficient of thermal conductivity, $\varkappa = c_t/c_v$ is the ratio of the heat capacity at constant pressure to the heat capacity at constant volume, and μ and ν are the dynamic and kinematic viscosity coefficients.

The similarity-criterion system (6) is more general than that which follows from the Boussinesq equations, which are usually used in analyzing convection in the surface layer of an atmosphere. It is assumed in the latter equations that density is independent of pressure and a linear function of temperature, with consideration of the density variation only in the lifting force. The criterion C_F in (6) is the ratio of the velocity of free fall from a height $h = L$ to the velocity of sound. This criterion takes account of the height distributions of density and pressure and might be referred to as the gravimetric compressibility criterion. For a characteristic dimension L close to the height H of the homogeneous Venusian atmosphere, $C_F \sim 1$. Values on this order can be modelled in numerical calculations of the complete Navier-Stokes equation system [10].

The criterion K determines the motive force of the convective motions in the gravitational force field. It can be assumed equal to the ratio of the adiabatic temperature gradient to the temperature gradient that arises owing to the heat flux from the surface in the absence of motion of the gas (i.e., at purely radiative equilibrium)*

$$K = (\partial T / \partial y)\mathrm{ad} / (\partial T / \partial y)\mathrm{rad}$$

The numbers $\varkappa$ and Pr determine the physical properties of the gas. The Rayleigh number Ra is a fundamental similarity criterion that takes account of the effect of viscosity in convective motion in an external force field.

The boundary defining loss of equilibrium stability will be represented by a certain curve in the Ra, K plane. In this case, the strength of the convective motions in the atmosphere will depend on the distance of the point Ra, K (which characterizes the specific conditions) from the stability boundary (Ra, K) and is, in the general case, a function

$$\frac{v}{\sqrt{\varkappa R T_1}} = f_1(\mathrm{Ra}, K, C_r, \mathrm{Pr}, \varkappa). \tag{7}$$

The convective motion intensity function (7) obtained in the calculations can also be presented in a different form:

$$\frac{vL}{\nu} = f_2(\mathrm{Ra}, K, C_r, \mathrm{Pr}, \varkappa), \tag{8}$$

where $f_2 = f_1 C_R$ and ν is the coefficient of kinematic viscosity. If we take the height $L = H \approx (10\text{–}12)$ km as the characteristic dimension of the region, the Rayleigh number will be $\mathrm{Ra} \sim 10^{21}\text{–}10^{22}$ in the lower layer of the Venusian atmosphere. At such large Rayleigh numbers, the convective motion is far beyond the mechanical-equilibrium stability threshold and is beyond question turbulent. Substantial difficulties are still encountered in numerical modelling with Ra in this region. And the difficulties of reproducing convective flows in laboratory experiments under these conditions are by no means minor. At the same time, numerical modelling of the remaining similarity criteria of (6) for the conditions of the lower Venusian atmosphere is impossible for smaller Ra.

2. <u>Statement of problem. Cellular convection model.</u> After loss of mechanical equilibrium stability, the convective motion in an infinitely long horizontal layer is broken up into a number of cells, each with a horizontal dimension close to the depth of the convection zone. The convection-intensity calculations were therefore performed for a single closed convection cell whose width L equals its height H.

---

*K will also be used below to denote the ratio of the adiabatic gradient to the actual (or assigned) gradient.

We considered only stationary solutions obtained by establishing the initial perturbations in calculating the system of nonstationary Navier-Stokes equations, which was done by the difference method [10]. Details of the calculation of convective motions of a compressible gas after loss of mechanical equilibrium stability with an assigned temperature difference across the cell are treated in greater detail in [10].

3. Analysis and discussion of results of calculation. Figure 5 presents an example of temperature-distribution calculation for a convection cell for the following values of the similarity criteria: /287

$$\mathrm{Gr}_L = 10^6, \quad C_r = 1, \quad K = 0{,}56, \quad \varkappa = 1{,}4, \quad \mathrm{Pr} = 0{,}71. \qquad (9)$$

In the figure, 1 is the initial profile corresponding to the radiative equilibrium profile in the lower layer of the atmosphere; 2 is the adiabatic temperature profile corresponding to the condition K = 1; 3 is the temperature profile obtained as a result of steady-state convective motion.

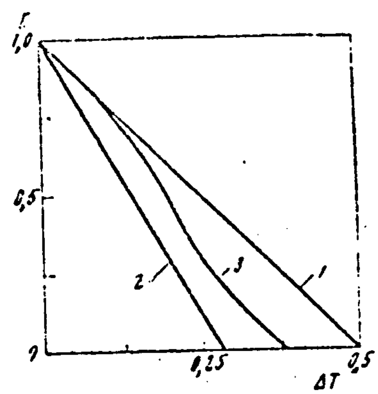

Figure 5. Vertical Distribution of Temperature in Convection Cell.

1) Initial Profile; 2) Adiabatic Profile; 3) Convective Profile.

The developed convective motion mixes the gas in such a way that a near-adiabatic temperature gradient is established in the core of the convective motion. However, the temperature gradient is greater than adiabatic in gas layers near the surface. The surface temperature T_s lies between the temperatures corresponding to the adiabatic and radiative profiles.

In reality, the convective motion in the atmosphere is penetrating in nature. This means that the upper limit of the convection cell is not fixed, but tends to move upward, and that profile 3 approaches profile 2 under steady-state conditions in this case. Nevertheless, calculations performed on the basis of the model of a convection cell with fixed boundaries can be used to estimate the intensity of penetrating convection as a function of the excess of the real temperature gradient over adiabatic.

Two limiting cases that model the development of convective motions in the atmosphere may be of greatest interest. The first corresponds to relatively weak convective activity and a quiet atmosphere, in which case the actual temperature gradient is near-adiabatic. The second case may correspond to maximum convection intensity, which occurs when an initial temperature profile close to the radiative equilibrium profile existed in the atmosphere at a certain time (Fig. 4).

In this case, if the viscosity of the gas is left out of account, the intensity of the convective motion is found to be much higher and can be presented in the dimensionless form

$$v / a_1 = \sqrt{2(1-K)C_F} \quad (a_1 = \sqrt{\varkappa R T_1}). \tag{10}$$

This estimate is analogous to [11] provided that the mixing distance equals the depth of the unstable layer and corresponds to the vertical dimension of the convection cell.

A comparison of this result with the result obtained when the gas viscosity is taken into account appears in Fig. 6. The dashed line 1 indicates the variation of convection intensity as a function of the ratio of the adiabatic temperature gradient to the assigned radiative gradient without consideration of viscosity according to (10).

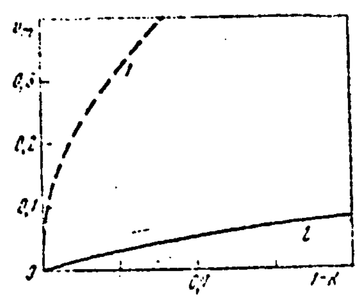

Figure 6. Comparison of Convective-Motion Intensities Without (1) and with (2) Consideration of Viscosity.

The results in Fig. 6 permit a qualitative estimate of convective intensity in the lower atmosphere of Venus in the two extreme cases examined above if it is assumed that the convective intensity is determined basically by the parameter K. We see from Fig. 6 that in our first extreme case, substantial vertical velocities may correspond to small deviations from statistical equilibrium (the condition for which is K = 1 in a quite atmosphere). Thus, for example, with K = 0.99, which corresponds for $(\partial T / \partial y)_{ad} \approx 8.5$ deg/km to a 0.1-deg/km deviation from the adiabatic gradient, the maximum intensity of the convective motions in the scale L of the convection cell may reach 1.5 m/sec. However, if viscosity is left out of account, the vertical-velocity value corresponding to K = 0.99 is found to be much higher, about 40 m/sec, which appears improbable for the values of the gas variables at the surface of Venus.

The results of calculation of the convection intensity can also be represented, according to (8), in the dimensionless form

$$\frac{v_m L}{\nu}(K) = \frac{v_m}{a_1}(K) C_n = 1{,}41 \cdot 10^3 \frac{v_m}{a_1}(K). \tag{11}$$

Since the real range of Ra was not modeled in the calculation, quantitative results can be obtained only by estimation of the turbulent viscosity v_t. To this end, we shall use the Richardson-Obukhov empirical law [12, 13], according to which

$$\nu(L) \sim \varepsilon^{1/3} L^{4/3}, \tag{12}$$

where L is the characteristic dimension and ε is the average specific rate of dissipation of kinetic energy in the form of heat by friction. When this relation is used, the intensity of the convective motion will take the form

$$\frac{v_m L}{\nu_t} = \frac{v_m}{(\varepsilon L)^{1/3}} = f(K). \tag{13}$$

The values of the functions

$$f(K) = 1{,}41 \cdot 10^3 \frac{v_m}{a_1}(K)$$

are determined in the calculations. The value calculated by Brent [14] for ε in the earth's troposphere is about 5 cm^2/sec^3. Assuming that ε is of the same order for the convective layer of Venus, we obtain for $L \sim 10^4$ m

$$v_m \approx 1{,}7 f(K)\,\mathrm{m/sec}. \tag{14}$$

Hence we have $v_m \approx 10$ m/sec for K = 0.99. Needless to say, these estimates hold only under conditions corresponding to our modeling in terms of similarity.

The real value of K must be estimated to evaluate the intensity of convective motions that may occur in the lower Venusian atmosphere under the conditions corresponding to the results of measurement. The order of magnitude of this quantity can be estimated from the measured values by use of the following approximate expression for the convective heat flux:

$$q_k \sim \rho c_p v \overline{\Delta T}. \tag{15}$$

Here $\overline{\Delta T} = \overline{T - T_{ad}}$ is the average difference between the real and adiabatic temperatures in the cell. Substituting into it the equation for the vertical velocity /289

$$v \sim \sqrt{\frac{2gH}{T} \Delta T}, \tag{16}$$

we obtain a formula for the average temperature difference in the form

$$(\overline{\Delta T})^{3/2} \sim \frac{q_k}{\rho c_p \sqrt{2gH/T}}. \tag{17}$$

At convective heat fluxes $q_k \sim 100\text{-}200$ kcal/m^2-h (see Fig. 5) and the average values of ρ and T over a convection-cell height $H \sim 10^4$ m ($\rho \sim 25$ kg/m^3, $T \sim 600^\circ$K, $C_p \sim 0.24$ kcal/kg-deg), we obtain $\Delta T \sim 5 \cdot 10^{-3}$deg. Hence $1 - K \sim \Delta T / T \sim 10^{-5}$. In the range of values of 1-K from 0 to 10^{-2}, the function v_m/a_1 (K) is approximately linear:

$$\frac{v_m}{a_1}(K) \sim 0{,}6(1 - K),$$

whence we obtain $v_m \approx (0.05\text{-}0.1)$ m/sec.

According to the estimate (10), we have for these values of K

$$v_m \approx (6 \div 9) \text{ m/sec}.$$

The estimate of (11)-(14) yields

$$v_m \approx (0{,}5 \div 1) \text{ m/sec}.$$

For estimation of the convection intensity in the other extreme case, Fig. 7 shows the altitude distribution of the parameter K calculated from local values of the temperature-profile gradient corresponding to radiative equilibrium (Fig. 4) and the value of the adiabatic temperature gradient in the Venusian atmosphere according to [3]. The diagram on the right in Fig. 7 shows the possible variation of the convective-motion intensity with height in the second extreme case according to the calculated results.

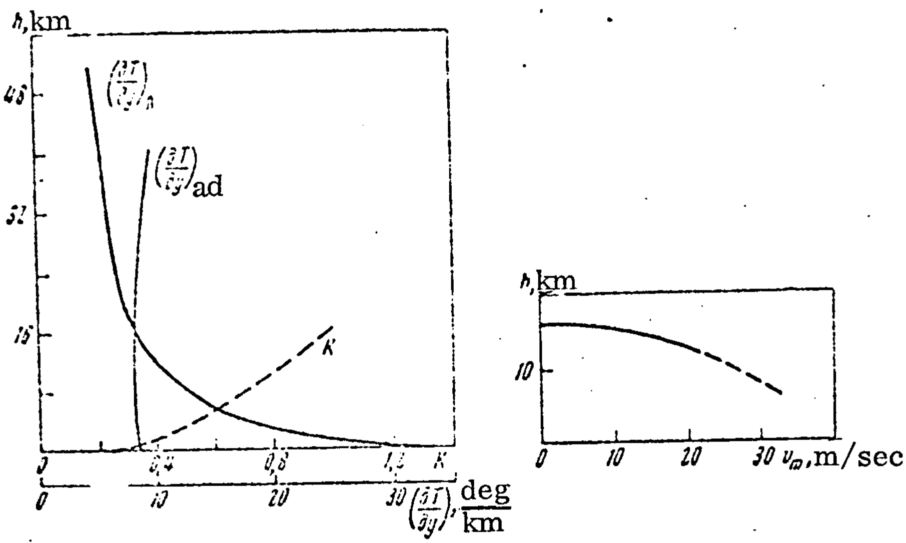

Figure 7. Estimated Variation of Convective-Motion Intensity with Height.

As we see, the convective-motion intensity rises rather sharply with the approach to the surface, where the ratio $(\partial T / \partial y)_{ad} / (\partial T / \partial y)_r$ reaches about 0.3 and the corresponding velocities of the convective motion may reach several tens of meters per second. The intensity of the convective motions decreases with increasing height and reaches zero at a height of approximately 15 km. However, the diagrams showing the radiant-flux distribution (Fig. 3) indicate that the influence of the convective motions should extend to greater heights, all the way to h $\approx$ 40-50 km. This fact may be linked to the penetrating character of the convective motions and to the reciprocal effects of radiation and convection. These factors and the influence of the large Ra were not taken into account in the convection model given here and must be made the subjects of further research.

CONCLUSION

Analysis of the thermal regime in the lower Venusian atmosphere for the values of the gas variables measured by the Venera 4, 5 and 6 unmanned probes makes it possible to derive certain estimates corresponding to a model with radiative and convective heat exchange.

The outgoing-radiation fluxes were calculated for selective radiation in the interval of wave numbers ν from 500 to 700 cm^{-1} with consideration of the angular distribution of the radiation field under various assumptions as to the percentage content of water vapor and the optical properties of the clouds. The plane layered model adopted incorporates the hypothesis of transparency of the Venusian atmosphere for the short-wave region of the solar spectrum. Available data on the absorption coefficients of CO_2 and H_2O and their temperature variations were used. The possible effects of Rayleigh and aerosol scattering were disregarded.

The calculated results lead to the conclusion that if the carbon-dioxide atmosphere does not contain water vapor, radiative transfer of heat from the surface is unrealistically large, considerably in excess of the value corresponding to radiation at the cloud tops at the effective temperature of the planet. Naturally, we may not exclude the possibility that the real pressure and temperature dependence of the absorption coefficients may cause covering of the transparency windows characteristic for CO_2 under normal conditions and change these estimates. At an H_2O concentration $\leqslant 1\%$, a balance can be struck between the heat arriving at the planet from the sun and the heat radiated by its atmosphere only on the assumption that the albedo of Venus $A \leqslant 0.6$, which does not agree with the results of albedo determinations from photometric measurements. Thermal balance may be arrived at for the most reliable values, $A \sim 0.75$-0.8, if it is assumed that $p \sim 0.5$, i.e., that about 50% of the outgoing radiation is reflected by the cloud layer of Venus.

The radiant fluxes determined from the measured temperature profile are variable with height and diminish appreciably toward the surface. The calculations indicate that radiative equilibrium is ensured only at heights above 40-50 km. Thermal equilibrium can be ensured at lower heights only by additional heat transfer. Since the measured temperature profile is near-adiabatic, transfer of heat by natural convection must be considered most probable.

Estimates of convective activity in the lower Venusian atmosphere were undertaken. For a cellular convection model with characteristic cell dimensions of the order of the homogeneous-atmosphere height, the Navier-Stokes equations were solved for a compressible gas with $Ra \leqslant 10^6$, and it was shown that the maximum intensities of the convective motions may reach 1.5 m/sec. Obviously, these estimates will hold only under conditions corresponding to our model which is based on similarity parameters. Other independent estimates, corresponding to a driving force (defined as the ratio of the adiabatic to the real temperature gradient) fitting the measured variables of the lower Venusian atmosphere lead to convective-motion intensity of the order of 0.1-0.5 m/sec.

REFERENCES

1. Avduyevskiy, V. S., Marov, M. Ya. and M. K. Rozhdestvenskiy. Kosmich. Issled., 7, No. 2, 233 (1969).
2. "Pravda," issue of June 4, 1969.
3. Avduyevskiy, V. S., Marov, M. Ya. and M. K. Rozhdestvenskiy. "The Tentative Model of the Atmosphere of the Planet Venus based on the Results of Measurements of Space Probes Venera 5 and Venera 6," Report presented at the Symposium on Atmospheres and Surfaces of the Moon and the Planets, Woods Hole, Mass., USA, 11-15, August 1969.
4. Avduyevskiy, V. S., Marov, M. Ya., Noikina, A. I., Polezhayev, V. I. and Zavelevich, F. S. "Thermal regime and convective motions in the lower atmosphere of Venus," Paper at symposium on the Moon Planets, Kiev, 15-22 October 1968.
5. Allen, K. W. Astrophysical Quantities [Russian translation], Izd-vo Inostr. Lit. (1960).
6. Malkmus, W. "Infrared emissivity of carbon dioxide (4.3 mkm) band," Opt. Soc. USA (1963).
7. Ferrisot, C. C., Ludwig, C. B. and A. L. Thomson. J. QSRT, 6, No. 3, 241 (1966).
8. Irvine, W. M. J. Atmos. Sci., 25, No. 2, 610 (1968).
9. Feigel'son, E. M. Trudy GGO, No. 166 (1964).
10. Polezhaev, V. I. Izv. Akad. Nauk SSSR, Mekhanika Zhidkosti i Gaza, No. 2 (1967); No. 5 (1968).
11. Schwarzschild, M. The Structure and Evolution of Stars [Russian translation], Izd-vo Inostr. Lit. (1961).
12. Richardson, L. F. Proc. Roy. Soc., A110, 709 (1926).
13. Obukhov, A. M. Izv. Akad. Nauk SSSR, Ser. Geografo-Geofiz., 5, No. 4-5, 453 (1941).
14. Brent, D. Physical and Dynamic Meteorology, Gostekhizdat (1938).

Translated for the National Aeronautics and Space Administration by Scripta Technica, Inc. NASW-2036.